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# Green and Safe "By Design": A Conceptual Tool to Avoid Hazardous Substances in Early Phases of Product Development

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**Abstract:** Sustainability has to be managed in order to guarantee health, social equity, resource optimization and economic activities and this awareness is grown considerably. At the same time, this consciousness leads us to consider sustainability also as a social and a business driver on the economic side and a great opportunity by an environmental point of view. Further, according to several regulations, producers are responsible of their devices in terms of environmental pollution, from production and market launch to disposal activities when they become unusable. This fact changes the role of designers, which becomes wider in a multidisciplinary context. For this reason, this paper proposes an approach that supports designers during the development of more sustainable products with the aim to reduce the amount of hazardous substances (according to European RoHS regulations) and it allows firms and academic R&D departments to reduce risks of a missing compliance. The approach is structured according to a flowchart that addresses designers to more suitable product solutions in terms of environmental impact. The methodology applied to the case studies, in fact, show that an early assessment in first design phases allows developers to have safer and more sustainable product prototypes and its application can be proposed also during design courses in an educational context.

**Keywords :** EU RoHS, conceptual design, functional approach, sustainability

## 1. Introduction

The strategic importance of environmental sustainability is the basis of European dispositions such as RoHS (Restriction of Hazardous Substances, European Directive 2011/95/CE [1] updated with the annexes III and IV in 2021), which represents a great responsibility for firms [2]. Although products are characterized by eco-labels and several certifications in terms of energy consumption, chemical properties of materials and industrial processes, they are not often conceived to be sustainable by a global point of view, because environmental impacts are not controlled and defined in each stage of product, service or process lifecycle [3]. Therefore, technologists have to be supported by engineering approaches oriented to environmental sustainability.

Although several software companies offer Life Cycle Assessment (LCA) tools and some methodologies are present in scientific literature, herein the proposal is to investigate on sustainability at the first stage of product design, considering that designers are important stakeholders involved in product creation (such as managers, marketing specialists, several enterprise divisions, public institutions, control organizations, etc.). Previous studies highlight that the best moment to ensure compliance with environmental European Directives (i.e. RoHS, WEEE, REACH, Ecolabel, Energy Saving labels, etc.) is during the early product design phases [4] [5]. So, it is required to identify when a project team should start to tackle environmental issues, reasoning about emissions and considering that a device may be sold on a large scale. Moreover, it is necessary to identify the key parameters that characterize a product architecture, such

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as shapes, materials, technological processes and technical hypotheses related to product planning and policies. Therefore, an early environmental evaluation becomes a road to address sustainability for a product-service development process [2], [6]. In the light of the above, this study is focused on an integrated approach that involves conceptual design, a compliance control on hazardous substances (HS) and a proposal to avoid them. Disposal policies, pollution control and RoHS rules, in fact, should be considered as additional constraints that lead the achievement of better sustainable solutions for every device, service or technological process.

## 1.1 A Brief Background

Design choices have a great impact on manufacturing, logistics, marketing policies and environment for every type of device; these decisions will also determine issues that need to be managed throughout a product lifecycle. Therefore, it should be necessary to face all factors that may generate energy dissipations, environmental, social and disposal problems, especially if a suitable reverse logistics system is not available [7]. In particular, the ranking proposed in Fig. 1 shows the most preferable strategies for end-of-life issues prevention. One of the main goals is the diffusion of sustainable devices and services, but markets do not always change quickly. First of all, design methods have to evolve towards increasing environmental friendly models, in order to conceive products aligned to some main requirements, such as:

- Long-term durability;
- Modular components;
- Upgradability (Smart Products);
- Reusability;
- Removability;
- High Recyclability;
- Production and usage conditions that avoid dangerous substances.

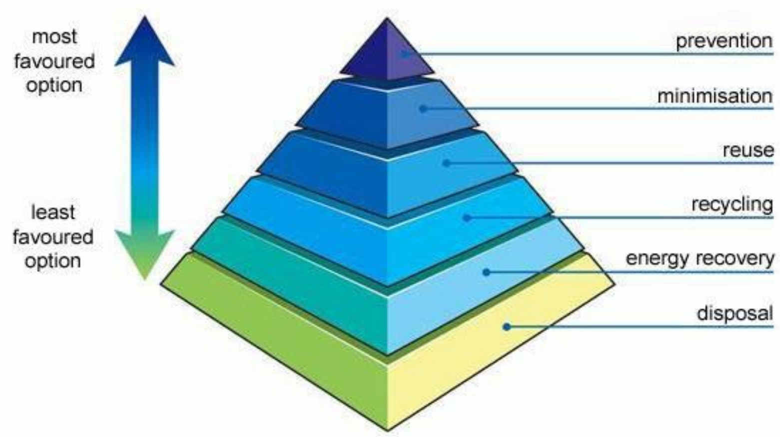


**Fig. 1 - Classification of favorite options for products end-of-life (Courtesy of ERFO, 2012)**

On the other side, a correct and sustainable "waste management" is necessary in order to avoid incineration and landfills, still in use unfortunately. Hence, it is necessary to propose products thought following eco-design guidelines and manage their environmental impact also when they will become obsolete. In this last phase, we need of technological systems ready to reuse them in other contexts or to transform them in secondary material supplies (see Fig. 2), in order to be compliant to an effective circular economy [8], [9], [10], [11]. This new paradigm (extremely required to face climate changes) can be effective when design, manufacturing, reverse logistics and regulations work together for the conception of "HS-free" products and services. Environmental issues related to products and services are characterized by two main aspects: i) eco-friendly products need time to be introduced into the market and to achieve the same (or a higher) success of the other ones already present; ii) a possible "near to zero" wastes strategy becomes achievable only if design activities, production cycles and the entire supply-chain are strictly connected to address sustainability goals (see Fig. 3). The adoption of reverse logistics models and green procurement to support material recovery and reuse (through the related reprocessing and transformation activities) is not yet systematic.

Some guidelines are useful during the conception of a first product layout, because they can represent a general set of requirements to be introduced in a whatever design process. Some main general rules can be cited [12] below:

- Reduce material intensity in product or service. It means less operations in logistics, less wastes to manage, less transportations;
- Reduce the energy intensity of the product or service (limit the consumption);
- Increase the amount of recycled and recyclable materials in the product;

- Use separable materials, in small numbers, preferring what it is required by the markets;
- Optimize the product durability, whereas it is not worthwhile to invest in short-term use products;
- Incorporate environmental features into the product;
- Focus on multifunction products, with adjustable power levels;
- Show product environmental features through physical design (e.g.: visible features of energy efficiency);
- Maximise the use of sustainable resources and supply chains. Use recycled materials in production, think about their origin and choice procurement materials that have high environmental performances;
- Optimise product performance and make users able to perceive its utility as more as possible;
- Look at the real lifecycle in detail with its sub-cycles and, then, design the product. Conceive products imaging their lifecycle, before sustainability issues arise at each phase and it is too late for design changes;
- Reduce the dispersion and the employment of hazardous substances and try to avoid unsafe emissions, despite some substances give some features to a product.

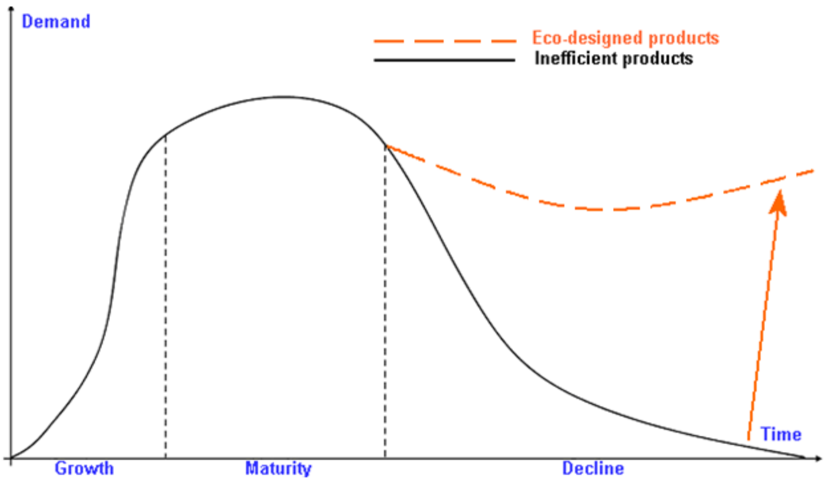


**Fig. 2 - Desirable commercial trend for eco-designed products (extended lifetime)**


**Fig. 3 - Simplified schema for a "near to zero" wastes strategy**

Together with these general guidelines, many methodologies have addressed the integration of environmental issues in product design in latest years [13] [14] [15] [16]. It is important to remember that environmental requirements have to be systematic by a green design point of view and they have to be translated into technical parameters in common practice. Moreover, a methodological approach to address design activities may be useful to achieve the goal of HS avoidance.

## 2. Materials and Methods: Approach Description

### 2.1 Conceptual Design Overview

The conceptual design is a particular phase of the design process in which technicians work with ideas, rough-shaped components and a low quantity of information. In this stage, many of the decisions related to shape, technological choices on materials and manufacturing processes are not completely taken [17]. Therefore, this fact aids the design team creativity. Generally, a design process is composed of three fundamental moments:

- the conversion of a need (or a set of needs) into a series of design specifications;
- the concept design, which is characterized by the ideation of physical solutions that meet project specifications;
- the detailed design phase, when final decisions are taken about geometries, functional shapes, materials and technological manufacturing processes.

The second one is the real creative phase, because proposals, ideas and contradictions often arise at "conceptual" level. If this stage is too brief and the project is not well analyzed, technical changes will increase and they may involve also the production phase. Therefore, it is very hard to conceive devices free of hazardous substances and reduce design gaps when it is too late. Furthermore, at the beginning of the conceptual phase a designer can propose ideas freely, because constraints are generally few, whereas opportunities to generate technical proposals decrease considerably in the detailed design phase. Some methodologies to assist conceptual design have been developed in latest years. One of the most appropriate techniques is the functional approach. It supports the creative process starting from the functional schematization of a technological system to the identification of product architectures [18], [19], [20], [21], [22].

A design team operates often in a 3D environment called “design space”, where both functional and geometric elements are combined together. Functional approach is characterized by the following elements: a design space, functional blocks, design objects (archetypes), links and the functional network [23]. This last structure is composed of boxes (connected to each other by links), which are transformed progressively into archetypes to be associated to specific components. More in detail, conceptual design process begins with the identification of the functions that a product has to perform according to specific functional requirements. Each function, which is expressed by a verb and a noun, is represented by a functional block, where one or more links occur on its surfaces (see Fig. 4). Afterwards, a greater level of detail is achieved with the transformation of functional blocks in 3D geometric elements (archetypes), to which classes of components can be associated. At the end of the process, the “design space” will be characterized by a set of archetypes connected to each other by functional links and they will constitute a preliminary product schema.

Graph formalization is also employed to describe functional networks [24], which are represented by a set of nodes (sub-functions/components) connected by links with a specific nature. Nodes and links are associated to classes of components that usually need to be managed in an appropriate system (such as a software database). Already in this conceptual stage, a design team can start to assess the environmental impact of a preliminary product layout, employing one or more methods available in the literature to support this activity [13], [25]. In such context, it is possible to integrate an approach useful to control the presence of hazardous substances.

## 2.2 A Conceptual Tool to Support Designers

A design team has to be supported in the selection of a product prototype that should be the best in terms of performance and environmental impact.

The approach flowchart summarized in Fig.5 (the schema employs a BPMN notation) starts when the design team is defining a first product layout by means of a functional net. At the beginning, the same developers propose a component archetype. If the design object already exists and it can be found on the market, the team will access to its properties by means of technical data, evaluating also chemical composition and the presence of particular hazardous substances (HS) with the aid of Life Cycle Inventories, environmental spreadsheets or complete LCA studies. Otherwise design objects are created by the project team or they are selected in an archetype database. Here, data related to environmental impacts are calculated by hypothesis using a LCA tool (e.g.: OpenLCA, SimaPro, GaBi, Eco Indicator ’99, etc.), which is useful as integrative data source, when information for that particular archetype is poor or rough.

Designers compare quantities of HS obtained by the assessment with tolerances present in updated RoHS tables for each real component or archetype, finding the following cases:

a. No HS in RoHS tables are present, then the component (or archetype) can be archived, it can be a candidate for design solution and designers can re-start to develop another part or sub-system;
b. HS are present in the component under consideration and they are lower than quantities allowed in RoHS tables (complete compliance);
c. HS are present in the component under consideration and they are within limits allowed in RoHS tables (the quantities are the same), so the component can be used but probably a further reasoning has to be made. Especially when an archetype has to be modeled, it is easy to exceed RoHS limits, because manufacturing processes are not completely defined (they may contribute to increase HS for several technological reasons);
d. HS are present in the component under consideration and they are out of regulation limits, then designers have to select another material or re-design that particular product part.

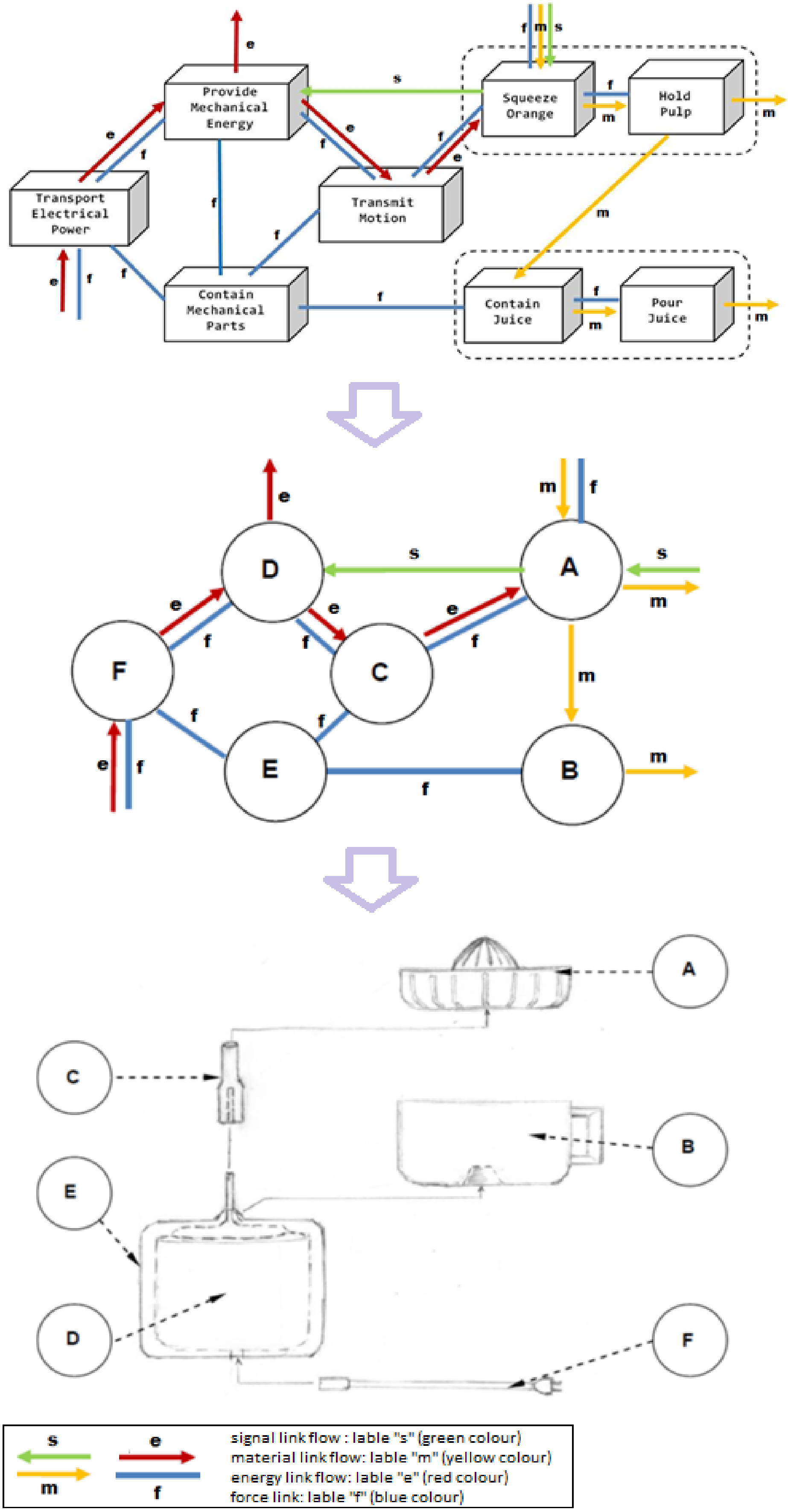


**Fig. 4 - Functional net of a squeezer (transition from blocks/graphs to the archetype sketches)**

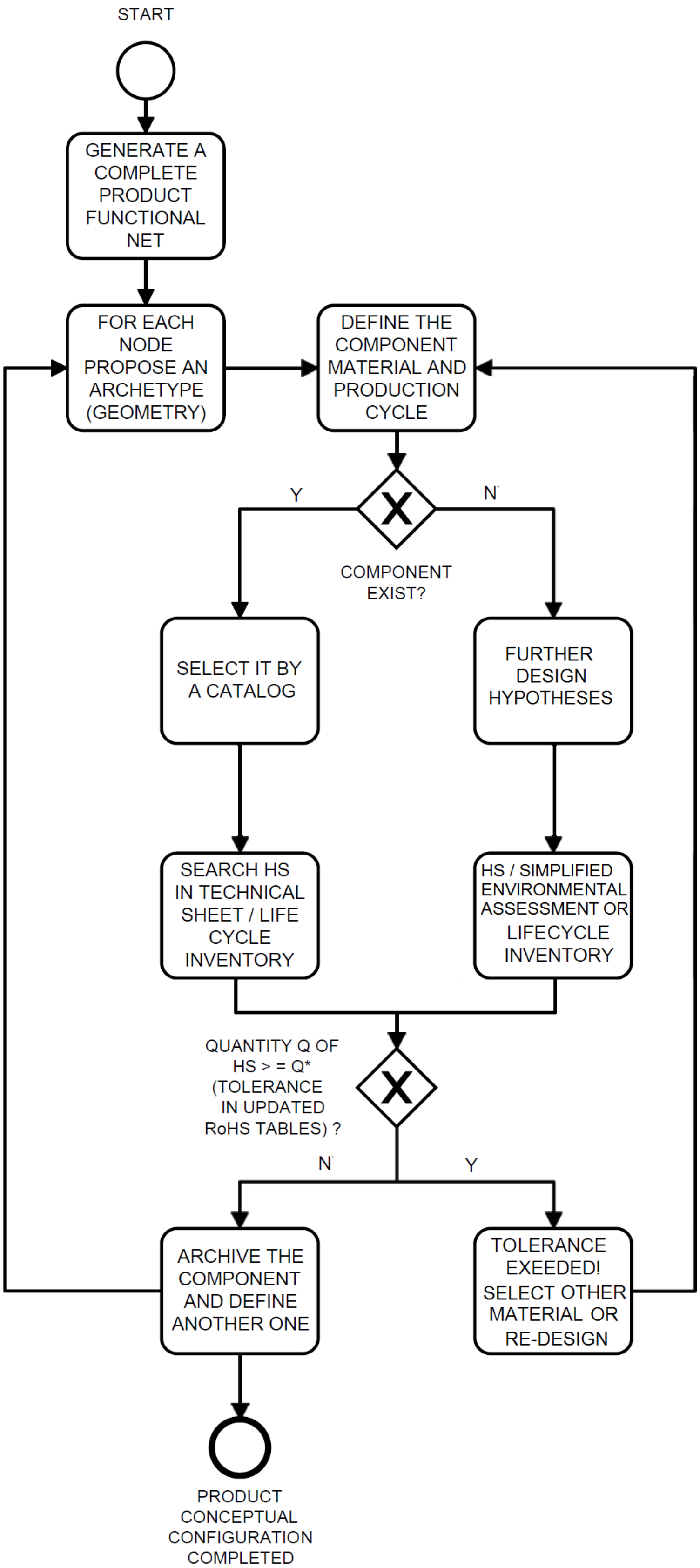


**Fig. 5 - Approach flowchart**

If a design solution is not available, designers have to use a CACD (Computer Aided Conceptual Design) software module to design it; afterwards the object will be saved as a new “archetype” in a database, which will be populated entering related information. Moreover, designers have to define the shape, the material and a set of substances proposed for the development. By a technological point of view, a hypothetical software tool could implement this approach in a tridimensional design space, where a specific software module reads values of physical/chemical composition of each archetype and performs a brief comparison between component HS and allowed limits present in RoHS tables. On a graphic interface, actions could be guided through advices represented by an icon in green color if tolerances are not exceeded, otherwise a yellow or a red symbol is displayed when threshold values are reached or they are over limits, respectively. Furthermore, a set of desirable system modules composing the entire computer environment can be represented by:

- A CACD (Computer Aided Conceptual Design) environment in order to support designer creativity;
- Functional blocks, links, forms/shapes and functional networks as 3D objects to be employed during the development;
- Database of archetypes and rough/detailed design solutions;
- Master Data DB supporting data sheets and documents such as LCA analysis and LCI inventories;
- Software integrators that allow to communicate with LCA tools (data import);
- Updated RoHS values that are digitalized as a table in the software database;
- Comparison methods and software functions (e.g.: APIs, code modules, queries);
- Suitable graphic user interfaces for designer activities and warning messages as advices on the screen.

It is important to observe that the methodology flow is placed during conceptual design phase and it can address designers to generate project solutions potentially free of pollutants and hazardous substances, because design freedom in searching of materials, shapes and technological processes is in line with eco-design guidelines. Therefore, developers can conceive products not only compliant with regulations, but even better in terms of “zero” or “near to zero” quantities of HS. This approach flexibility is discussed in the next section, where two case studies are presented.

## 3. Results and Discussions

The entire approach can be used in a real product development process, in order to better understand how the methodological steps are integrated in the common conceptual design practice, considering two different design scenarios with the aim to demonstrate its wide applicability.

### 3.1 Case Study 1

Figure 6 shows the conceptual design phase of a new “coffee grinder” by means of a functional approach, whereas figures 10 (a) and 10 (b) show the improvement of a simple clothes peg.

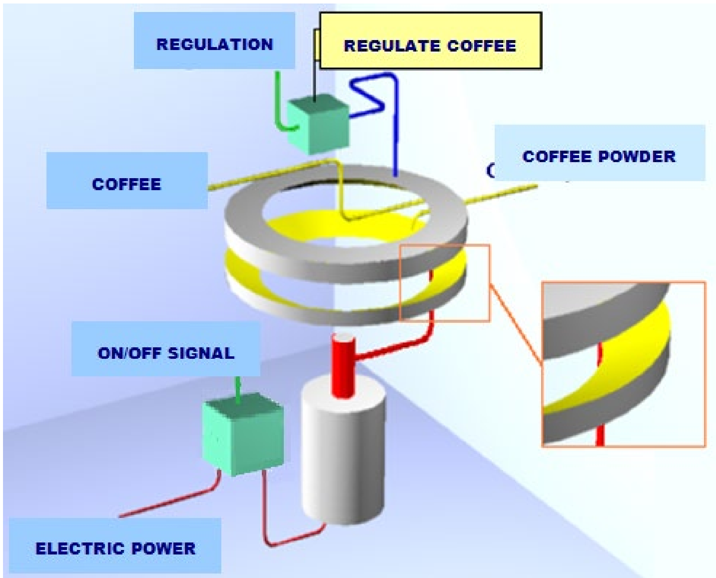


**Fig. 6 - Functional analysis of a coffee grinder (as step of the approach flowchart)**

In the first case study, a design team is focusing on the development of the “switch” (the box with the label “on/off signal”) and few components have reached the state of rough archetypes, although it is possible to understand the rough product architecture and the functional role of some shapes and design objects. Furthermore, in the same figure it is possible to analyze also the flows of material (yellow), force (blue), signal (green) and energy (red) of the entire product schema. At the beginning, the team selects an existent solution from the market, which is characterized by the properties and the materials showed in Table 1 and Fig. 7.

By the technical data sheet of this particular component, the design team finds that the switch is RoHS compliant, but some hazardous substances were used and threshold levels were not exceeded, even if only slightly. The team, then, decides to develop a new component (see Fig.8), even better in terms of ergonomics and environmental impact. In this phase, in fact, many prototypes can be generated and several hypotheses can be made about shapes, materials to be employed and production cycles for a completely HS-free product. In the light of this new second hypothesis, developers evaluate if HS levels may exceed the allowed thresholds for the new component (considering also materials and technological process) or the same HS may be totally avoided. At the end of the sketching activity, designers can start to define a different product component, selecting or creating another design solution for a specific product part and, then, performing the related environmental control check according to the approach proposed in Fig.6.

**Table 1 - Switch material specifications**

| Component | Material |
|---|---|
| Switch housing | Thermoplastic polyester |
| Actuator button | Thermoplastic polyester |
| Spring | Copper alloy |
| Pivot | Copper alloy |
| Movable contacts | Silver alloy |
| Stationary contacts | Silver alloy |
| Terminals | Copper alloy |
| Actuator lever | Stainless steel |

**Fig. 7 - Switch item model**

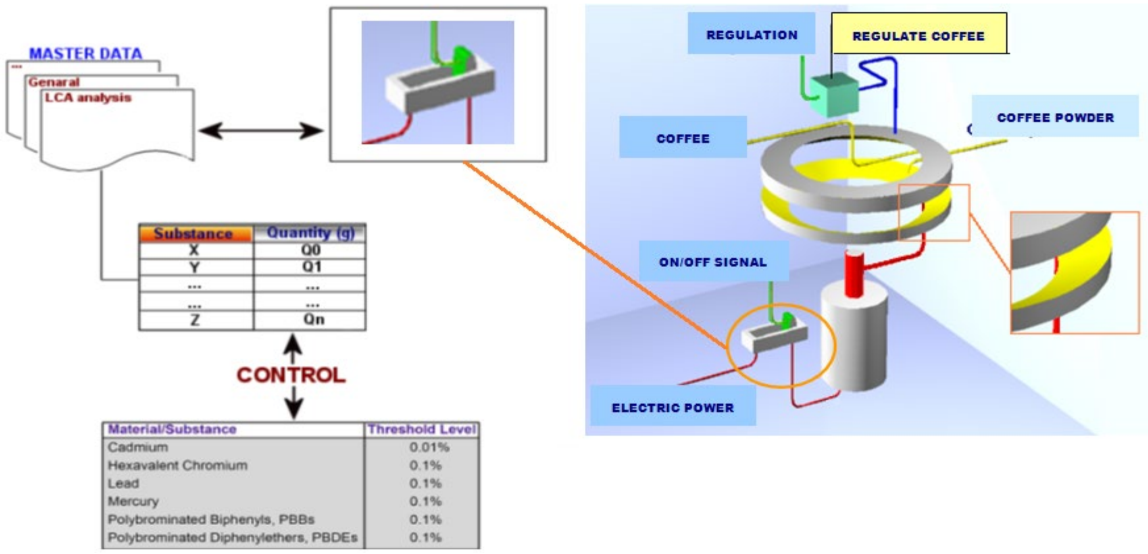


**Fig. 8 - Switch solution archetype during its development**

### 3.2 Case Study 2

A second example is provided by the development of a simple iconic device: a clothes peg. In this case, the approach flowchart is applied to a whole product instead of a single component. Herein, the project team aims to improve this product by an environmental point of view and in an early design process moment, when a functional net has already been defined (Fig. 9). Although there is only one functional net (and only force links are present), the team evaluates two concepts already existent on the market, which obviously present differences in terms of materials and shapes (see Table 2 and Fig. 10 a, Fig. 10 b).

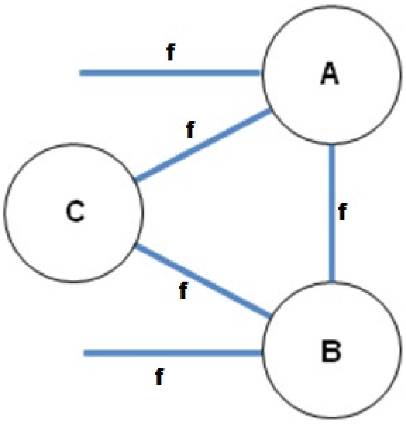


**Fig. 9 - A proposal of functional net for a clothes peg concept**

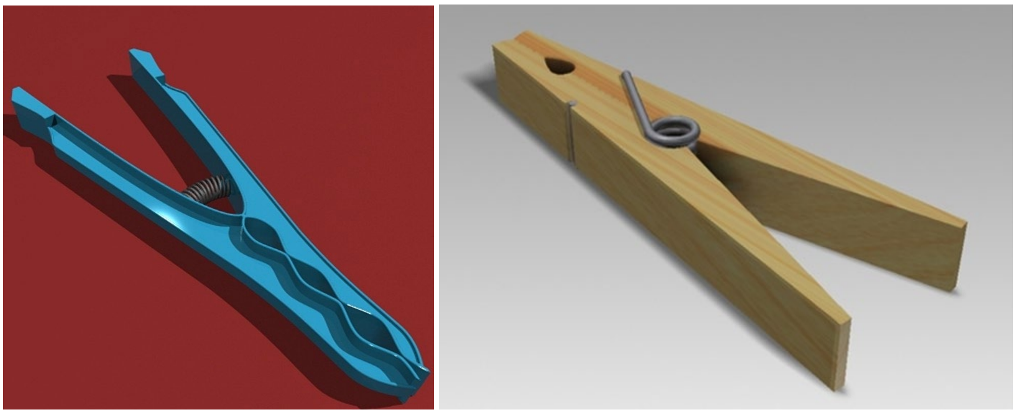

**Fig. 10 - Solution 1 (a) and solution 2; (b) cad/cacd models**

**Table 2 - Solution 1 and solution 2 specifications**

| Solution | Component | Quantity | Material | Main Processes |
|---|---|---|---|---|
| | A (Shaped Profile 1) | 1 | Polypropylene | Injection molding; Assembly |
| 1 | B (Shaped Profile 2) | 1 | Polypropylene | Injection molding; Assembly |
| | C (Spring) | 1 | Steel; Chromium | Drawing; Folding; Assembly |
| | A (Shaped Profile 1) | 1 | Wood | Cutting; Milling; Assembly |
| 2 | B (Shaped Profile 2) | 1 | Wood | Cutting; Milling; Assembly |
| | C (Spring) | 1 | Steel; Chromium | Drawing; Folding; Assembly |

Starting from these last embodied product concepts, the design team performs a streamlined or a complete LCA, evaluating possible environmental concerns. In particular, Solution 1 is made of polypropylene, which may produce environmental pollution if it is not correctly recycled and it often increases its structural frailty due to atmospheric agents and heat exposure. Solution 2 is made of wood and it can be lightened in terms of mass. In both cases, the two clothes pegs employ a spring. If this last component is a metallic item, it is often chromium plated or it is made of stainless steel, in order to prevent corrosion. Although chrome plating processes have been improved in the last years, the design team decides to move forward using an eco-design perspective:

- avoiding HS or materials that have a great impact on the environment on a large scale;
- reducing product mass (material usage);
- employing recycled wood;
- reducing/optimizing production cycles.

At this point of the concept design process, the designers generate an archetype sketch after a functional modeling by a CACD software (this development is not reported here, see coffee grinder example in Fig.6 and Fig. 8), as it is showed in Fig. 11 (Solution 3). The team continues the design process with the embodiment phase of a more defined 3D CAD model, which has to be suitably engineered (e.g.: by a CAE software tool) before a real prototype creation, verifying also its mechanical performance and efficacy. According to the approach described in Figure 5, this early design solution can be archived as a conceptual product model together with its additional design hypotheses: employment of recycled wood as construction material; conception of a lightweight "single component" product; cutting and milling as main production processes.

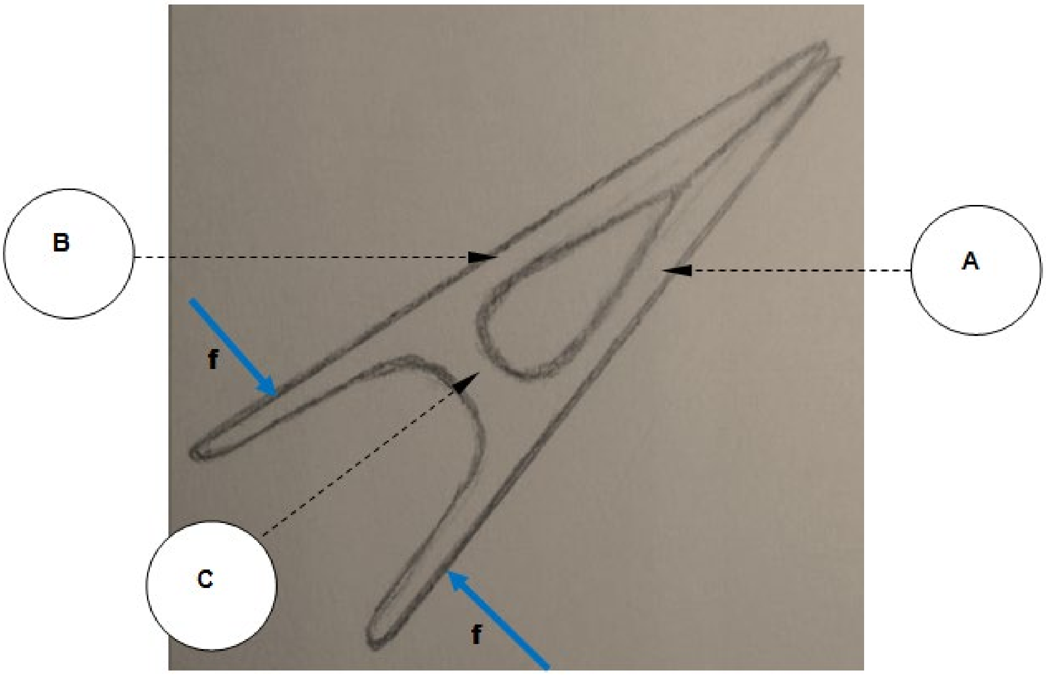


**Fig. 11 - Solution 3 archetype sketch**

## 4. Conclusions and Future Outlooks

This paper was focused on the reduction of environmental impacts of products from the early stages of design process. The main aim of this study was the proposal of a methodological approach to support the conceptual design stage by an environmental point of view, considering that it could be implemented also in a computational context. First of all, sustainable product conception was presented as a good way to prevent environmental pollution together with some main eco-design strategies used as fundamental guidelines. Then, the need of environmental impact avoidance in a preliminary design stage was argued. Furthermore, the approach flowchart was described in its basic features (also as a possible software system) and two applicative examples were also discussed.

Findings suggest that an early assessment in first design phases allows developers to have safer and more sustainable product prototypes. The methodology applied to the case studies under investigation, in fact, shows that a design team is addressed to the best solution in terms of safety (HS avoidance) during conceptual design phase, when several hypotheses on shapes, materials and production processes can be made, without giving up creativity (see the two case studies in section 3). The approach, moreover, would reach better performance if combined with eco-design tools (e.g. A-DSM, Function Impact Matrix, etc.) and it could be included in several educational programs and design courses, in which more and more attention should be dedicated to design for sustainability. Moreover, it would be interesting to apply this same approach also to several technological processes, in order to design them, avoiding environmental issues as much as possible. In this way, firms and public R&D departments could mitigate the risk of missing compliance with the RoHS and other European directives also in these contexts.

As drawback, this approach may present some limitations, because it employs different data sources to perform environmental evaluations, which are based on lifecycle inventories in the stage of archetypes definition, when information is poor or rough. Moreover, further case studies could strengthen and validate the entire methodology. In the future, a new related work may be focused on the IT formalization of this conceptual tool, describing the software environment in detail, in order develop a software application module to support cleaner design and production. It is a long way to a real "Green Deal".

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## References

[1] Directive 2011/65/EU of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment. June 2011, (updated 2019)
[2] Avila G. (2006). Product development for ROHS and WEEE compliance. Printed Circuit Design and Manufacture, 23(5):28-31
[3] Horne R. E. (2009). Limits to labels: The role of eco-labels in the assessment of product sustainability and routes to sustainable consumption. International Journal of Consumer Studies, 33: 175–182
[4] Han, J., Jiang, P., & Childs, P. (2021). Metrics for measuring sustainable product design concepts. *Energies*, *14*(12), 3469.
[5] Ruy, M., Alliprandini, D., & Scur, G. (2019). Environmental assessment in the conceptual design phase of new product development. *International Journal of Sustainable Design*, *3*(3), 182-204.
[6] Rocco C. (2015). Aspects to Enhance Environmental Sustainability in Industry: A Brief Roadmap. Sustainability: the journal of record, 8 (5): 254-260
[7] Xavier L. H. and Correa H. (2013). Concepts, design and implementation of Reverse Logistics Systems for Sustainable Supply Chains in Brazil. Journal of Operations and Supply Chain Management, Vol. 6 Number 1: pp. 1 – 25
[8] Berger, F., Gauvin, F., & Brouwers, H. J. H. (2020). The recycling potential of wood waste into wood-wool/cement composite. Construction and Building Materials, 260, 119786.
[9] Muncke J, Andersson AM, Backhaus T, Boucher JM, Almroth BC, Castillo AC, Chevrier J, Demeneix BA, Emmanuel JA, Fini JB, Gee D. (2020). Impacts of food contact chemicals on human health: a consensus statement. Environmental Health. Dec; 19(1):1-2.
[10] Lee J, Pedersen AB, Thomsen M. (2014) The influence of resource strategies on childhood phthalate exposure—the role of REACH in a zero waste society. Environment international, Dec 1;73:312-22.
[11] Leslie HA, Leonards PE, Brandsma SH, De Boer J, Jonkers N. (2016) Propelling plastics into the circular economy-weeding out the toxics first. Environment International, Sep 1; 94: 230-4.
[12] McAloone T. C., Bey N. (2009) Environmental improvement through product development: A guide. Danish Environmental Protection Agency; Copenhagen, Denmark.
[13] De Napoli L., Rizzuti S., Rocco C. (2017) An integrated model for the environmental assessment of industrial products during the design process. Concurrent Engineering, 25(4): 360-380.
[14] Alemam A. and Li S., Matrix-based quality tools for concept generation in eco-design (2016). Concurrent Engineering: Research and Applications, 24(2): 113–128.
[15] Bohm MR. Haapala KR. Poppa K. et al. (2010) Integrating life cycle assessment into the conceptual phase of design using a design repository. Journal of Mechanical Design 132(9): 091005 (12 pp.).
[16] Devanathan S., Ramanujan D., Bernstein WZ. et al. (2010). Integration of sustainability into early design through the function impact matrix. Journal of Mechanical Design, 132(8): 41–48.
[17] Rocco C., De Napoli L., and Rizzuti S. (2011). A proposal for an augmented DSM to assess product sustainability. In: 13th international dependency and structure modeling conference (ed. SD Eppinger, M Maurer, K Eben, et al.), MIT, Cambridge 15–16 September 2011; pp. 45–57. KG, Munich: Carl Hanser Verlag GmbH & Co.
[18] Ulrich K. and Eppinger S. (2001). "Product Design and Development", McGraw-Hill, New York.
[19] Pahl G. and Beitz W. (1996). Engineering Design – a systematic approach, Springer, London.
[20] Cross N. (2000). "Engineering Design Methods", John Wiley & sons, New York.
[21] Suh N. (1990). "The Principles of Design", Oxford University Press.
[22] Hubka V., Eder W.E. (1992). "Engineering Design", Heurista, Zürich.
[23] Bruno F., Giampà F., Muzzupappa M., Rizzuti S. (2003) "A Methodology to support designer creativity during the Conceptual Design Phase of industrial products", Proceedings ICED03, Stockholm, Sweden.
[24] Rizzuti S. De Napoli L., Rocco C. (2006). A Graph-Based Approach to Check a Product Functional Net. 9th International Design Conference DESIGN 2006 Cavtat-Dubrovnik; pp. 111-119.
[25] Bovea MD. and Perez-Belis VA. (2011). Taxonomy of eco-design tools for integrating environmental requirements into the product design process. Journal of Cleaner Production; 20(1): 61–71.